Characterization And Control Of Aeroengine Combustion Instability:

Pratt & Whitney and NASA Experience

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Acknowledgements

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- PW/UTRC – (Platform Development and testing) Dr. Jeffery Lovett, Dr. Jeffery Cohen, Karen Teerlinck, Dr. Torger Anderson, Prabir Barooah, et al

- GaTech – (Actuator development) Dr. Ben Zinn, Dr. Yedidia Neumeier et al

- VaTech – (Control methods) Wil Saunders, et al

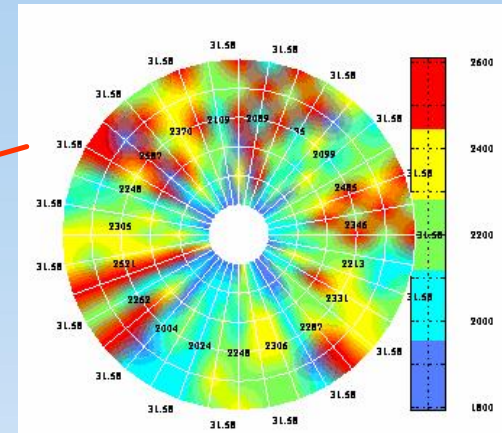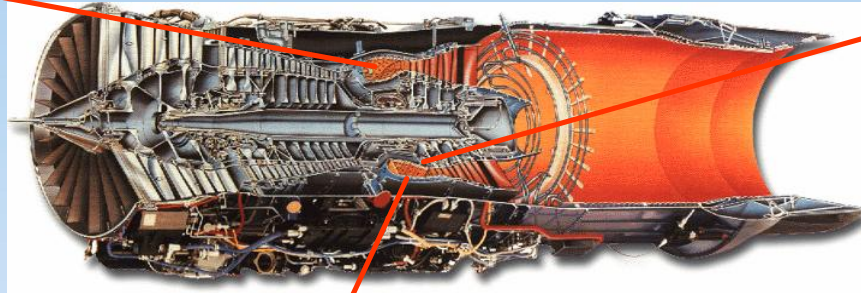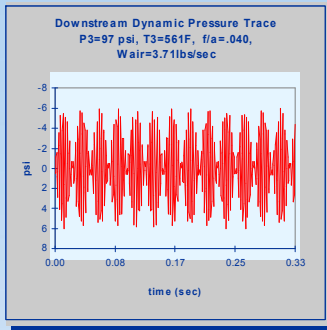- PSU – (Injector dynamics simulation) Dr. Vigor Yang
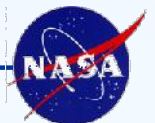
<u>Outline</u>

- NASA's Active Combustion Control interests

- Motivation: Ultra-low emissions, lean burning, MultiPoint-Lean Direct Injection (LDI) combustors

    - More susceptible to instability

- Our approach for dealing with combustor thermo-acoustic instabilities

- Outcome of our recent instability control experiments

- Technology transfer, future plans

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NASA Active Combustion Controls

Downstream Dynamic Pressure Trace
P3=97 psi, T3=561F, f/a=.040,
Wair=3.71lbs/sec

Combustion Instability Control

objective: actively suppress thermo-acoustic pressure oscillations

Pattern Factor Control

objective: actively reduce combustor pattern factor

Low-Emission Enabling Control

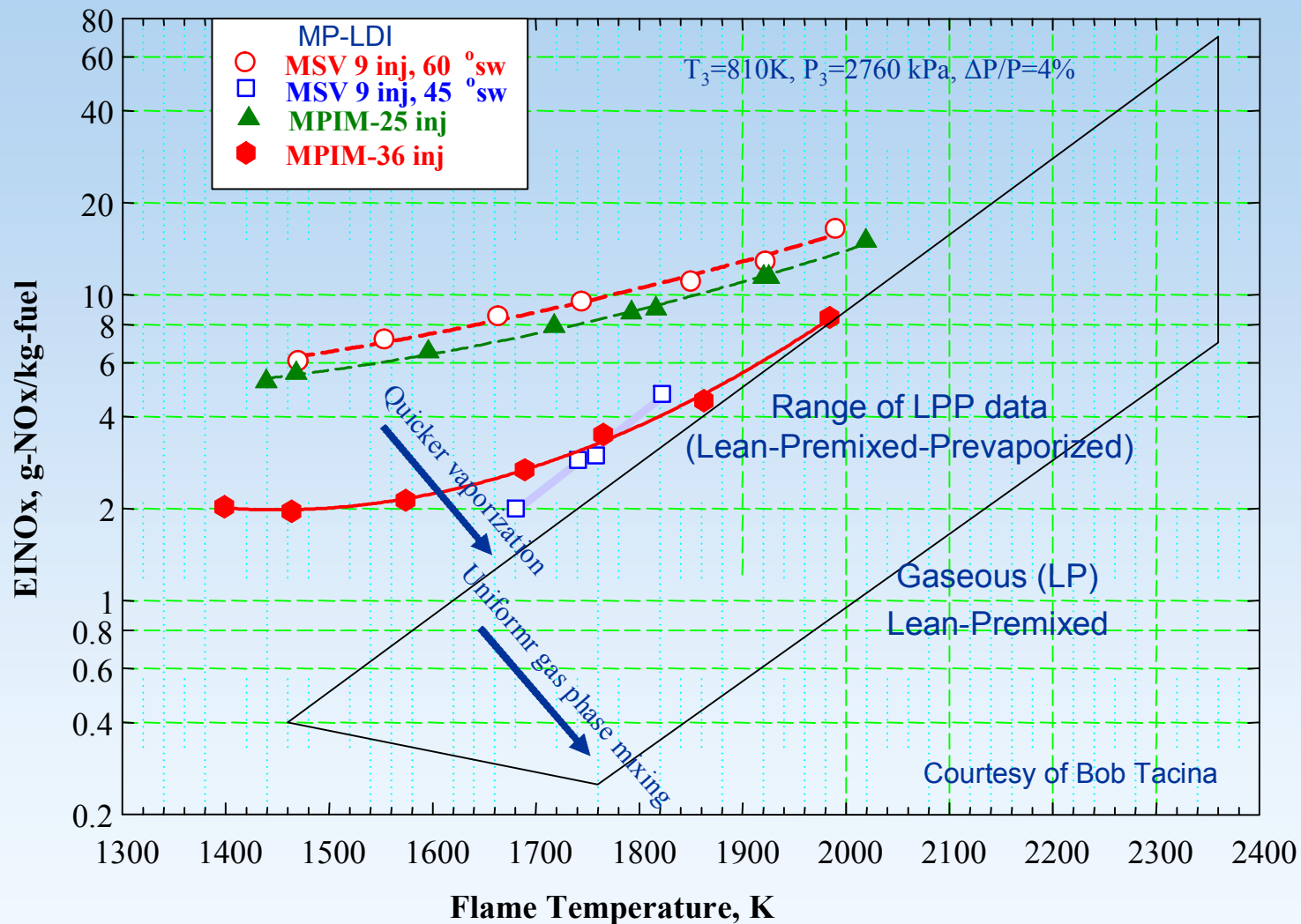**objective:** actively reduce NOx production

➢**Intelligent combustor with extremely low emissions throughout the engine operating envelope**
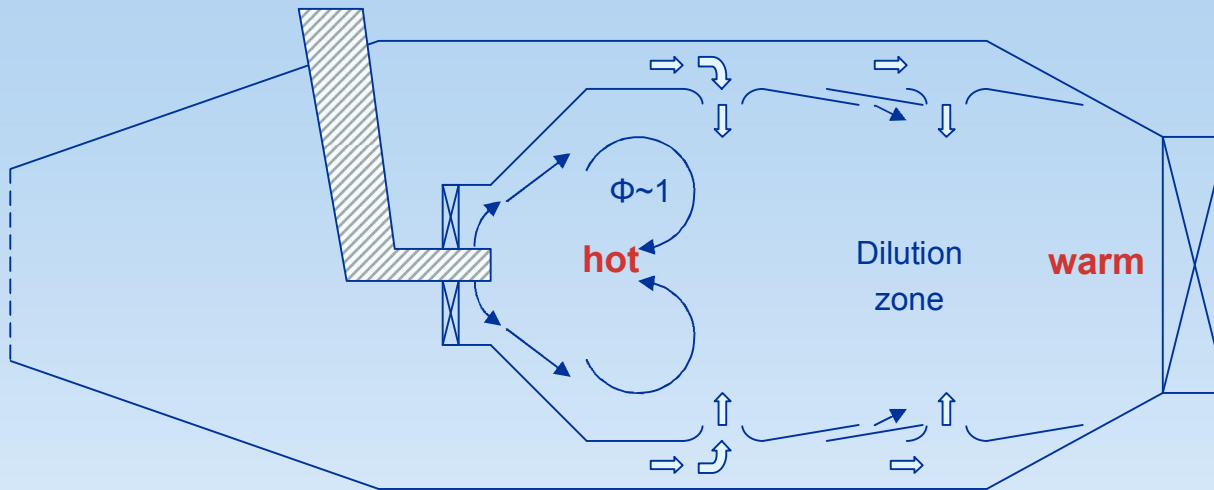
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Effect of Fuel Injection Schemes on NOx Emission

Advantages of Multi-Point Lean Direct Injection (MP-LDI)
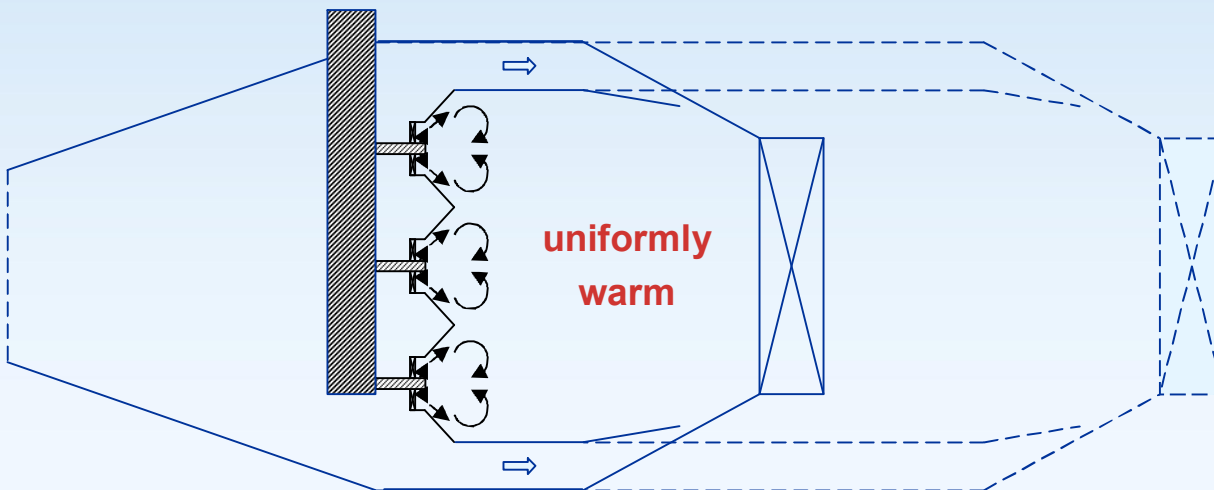

Lean & uniform front end
- Lower front-end temperature
- Little CO produced
- Shorter combustor
- Short residence time
- Reduced shaft length
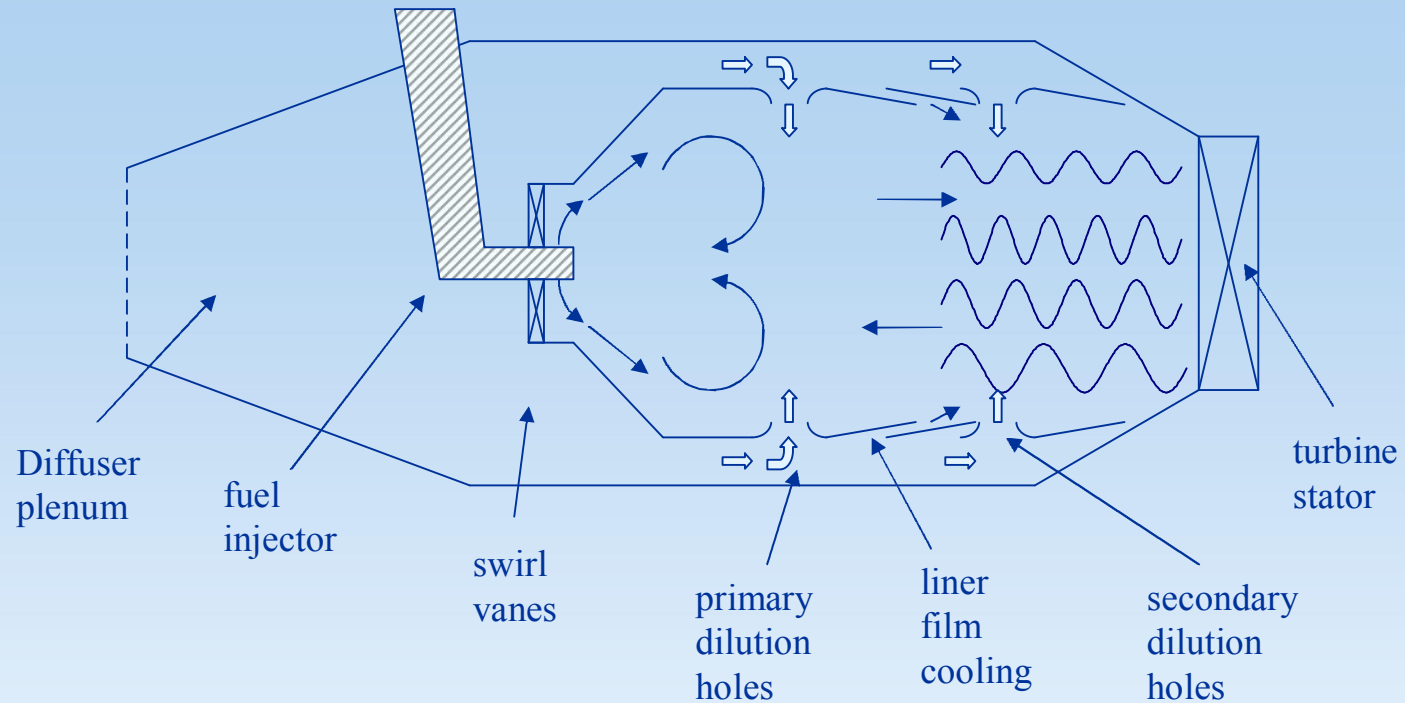- Low NOx produced
- Low smoke

Direct injection
- No flash back
- Operate at high temp.

Multi-point
- Short mixing time
- **Spatial fuel shifting**
- Low-power piloting
- Hot-streak elimination
- **Temporal fuel modulation**
- T-A instability control

Issues that Affect Combustor Instability / Acoustics

Diffuser plenum

fuel injector

swirl vanes

primary dilution holes

liner film cooling

secondary dilution holes

turbine stator

1. **Well-defined acoustic boundary conditions**
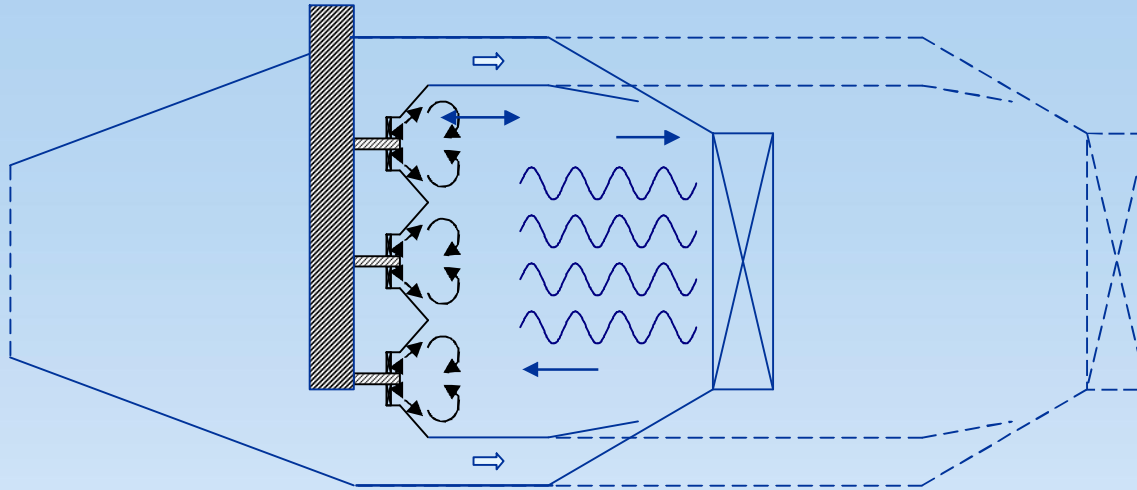
2. **Perturbations from fuel-nozzle turbulence**

3. **Recirculation vortex provides flame-holding**

4. **Liner film-cooling provides damping**

5. **Multiple temperature zones**

6. **Φ' interaction with P'**

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Why is Lean-Burning Combustor More Sensitive?

1. Higher-performance fuel injectors: more turbulence

2. Reduced film cooling: reduced damping

3. More uniform temperature and composition
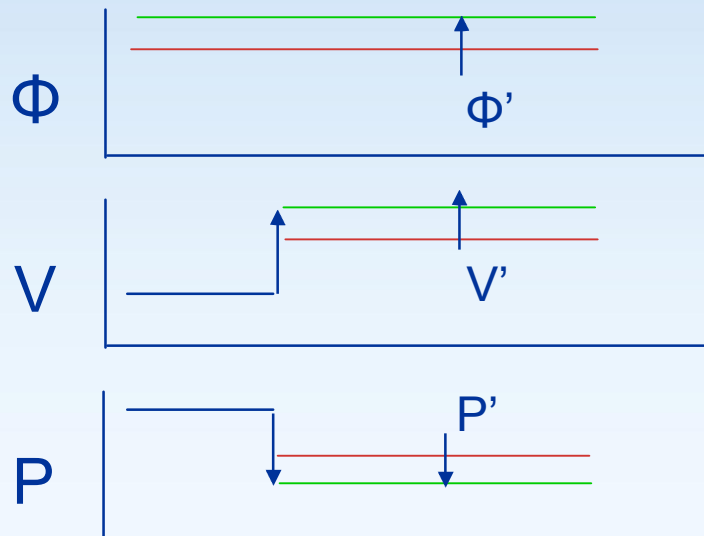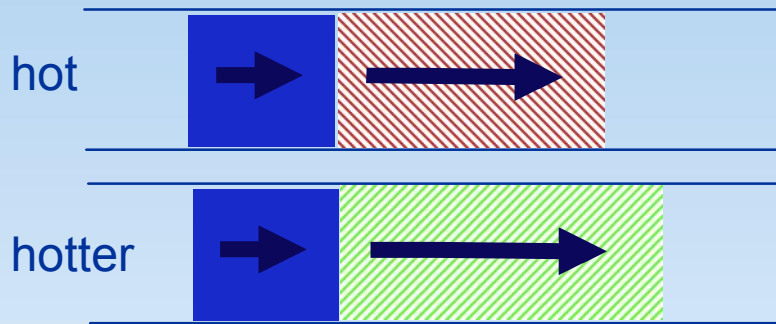
4. No dilution holes: reduced flame-holding
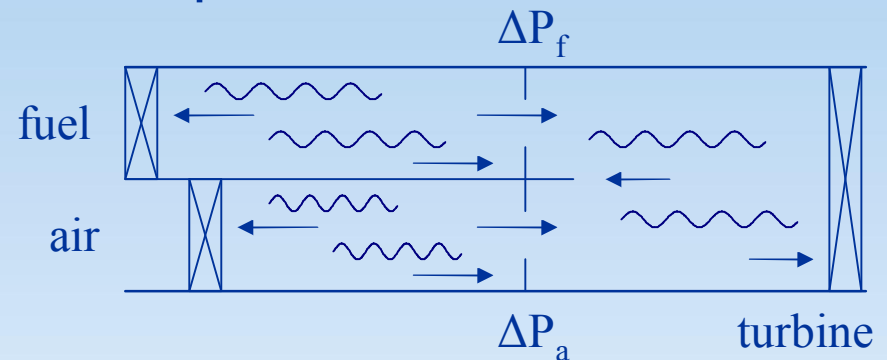
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How does heat release interact with pressure?

$\Phi' \Rightarrow P'$: Rayleigh loss

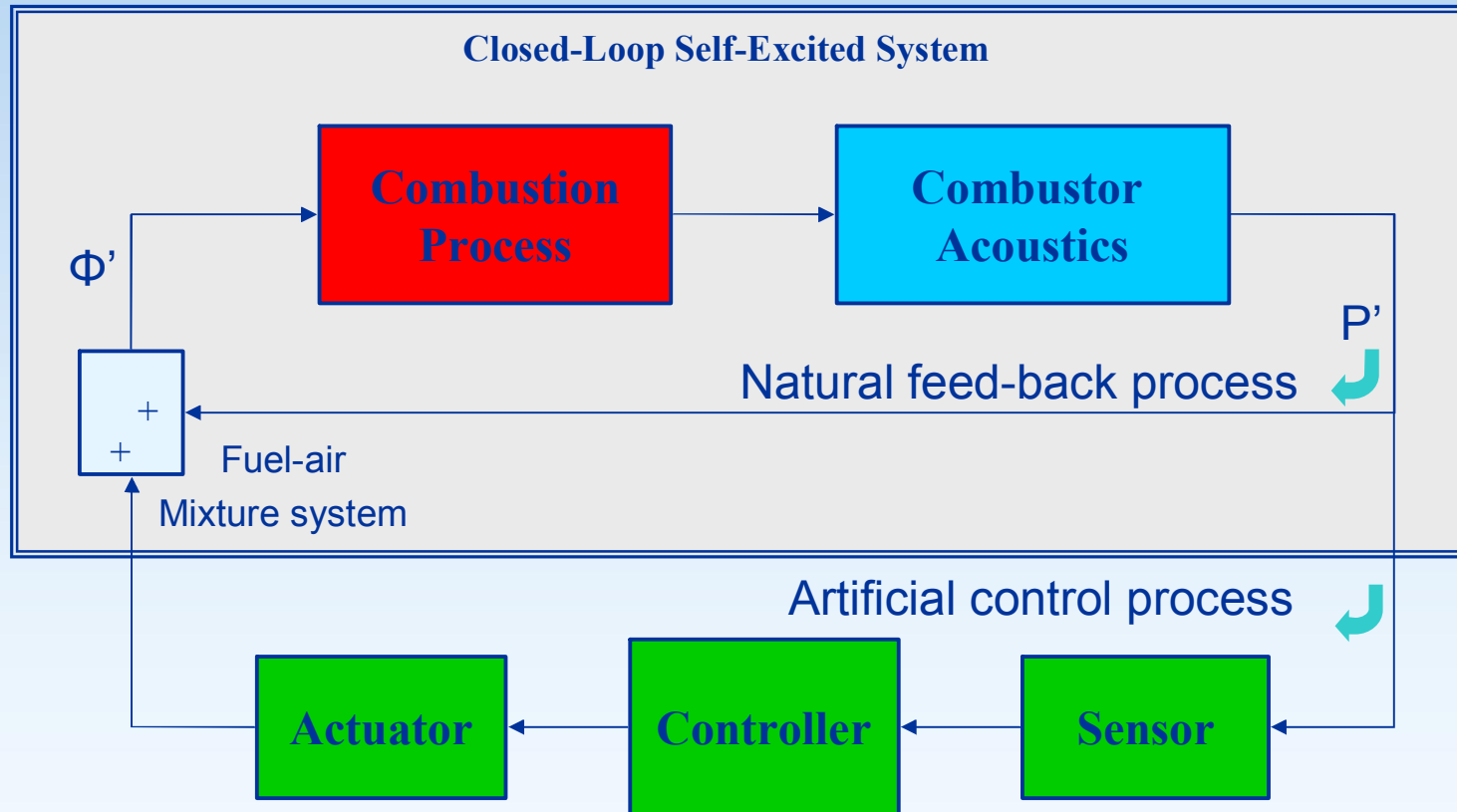$P' \Rightarrow \Phi'$: Feed system impedance mismatch

hot

hotter

Φ Φ'

V   V'

P   P'

fuel

air

ΔP_f

ΔP_a turbine

Static example	fuel	air
ΔP	40 psi	4 psi
mdot	~sqrt(40)	~sqrt(4)
$\Delta p'$	-1 psi	-1 psi
$\Delta p'/\Delta p$	1/40	1/4
1+mdot'/mdot	~sqrt(41/40)	~sqrt(5/4)

$\Phi'/\Phi \sim$ (mdot'/mdot)$_{fuel}$/ (mdot'/mdot)$_{air}$ -1
~sqrt(4/5)-1 ~ -0.1

NASA

Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur

How do we deal with combustor instabilities?

1. Smart design
2. Modulate air to get out-of-phase cancellation
3. Fuel-modulation to get out-of-phase cancellation

However…

Method 1 is preferred, but we're not sure it's enough.
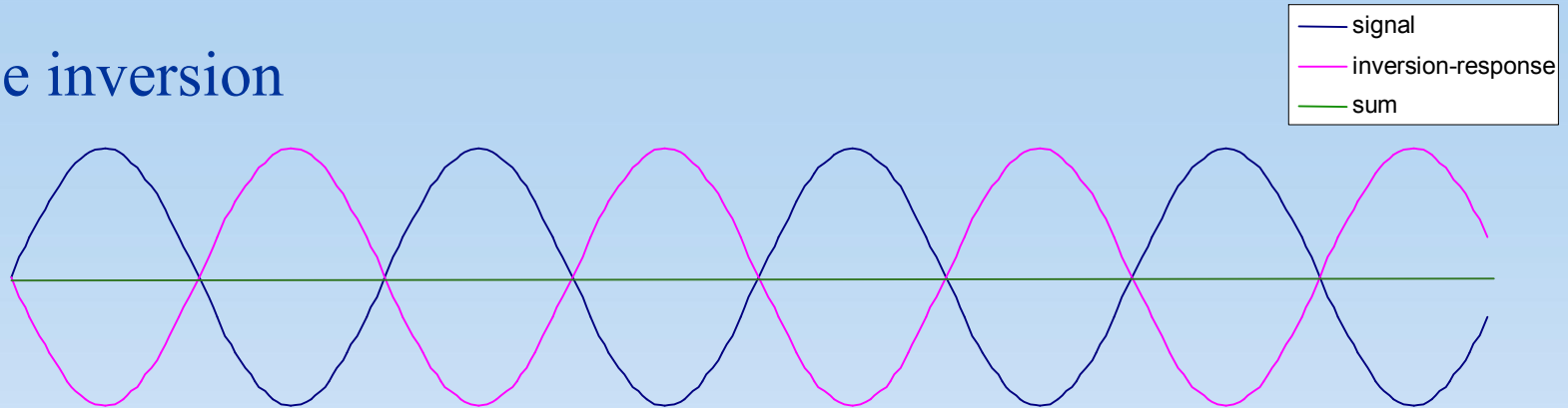Method 2 requires lots of actuation power input and bulk.
   Method 2 also may induce diffuser flow separation due to
   flow perturbation.
Method 3 requires the least actuation power and bulk and
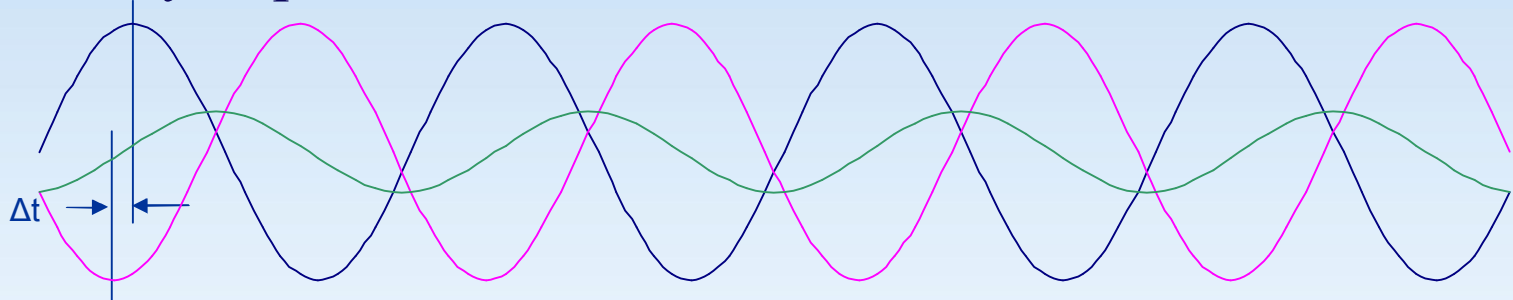   produces the most energy change.

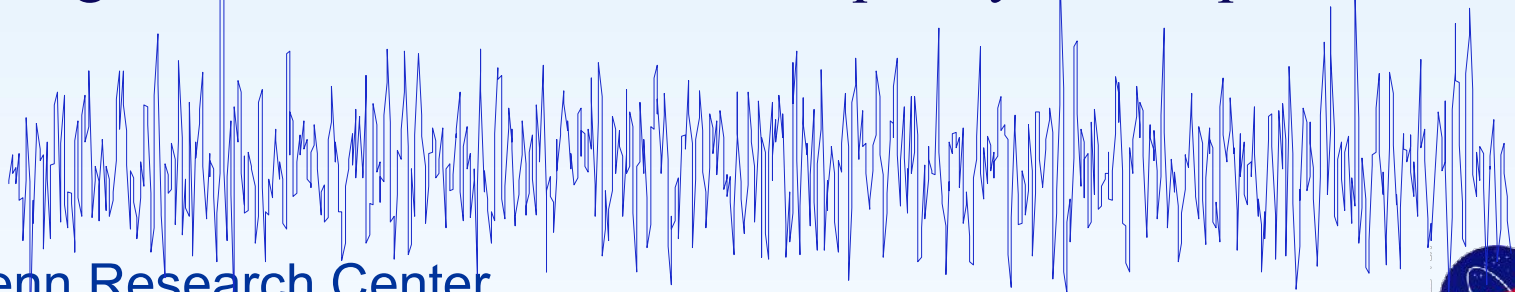# Why is instability control so difficult?

Phase inversion

Time delay & phase shift

Low signal-to-noise ratio – What frequency? What phase?

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Our Technical Challenges

- Combustor dynamics largely unmodeled

- Liquid fuel – introduces additional unmodeled dynamics including time delay (atomization, vaporization, …)

- Actuation system – enough bandwidth and authority, not just valve (also feedline, injection, …)

- Experimental testbed for actuation, feedline dynamics required

- Simplified models needed for control design evaluation

- Control methods required to:
  - identify instability
  - suppress instability in presence of large time delay, substantial noise, unmodeled dynamics
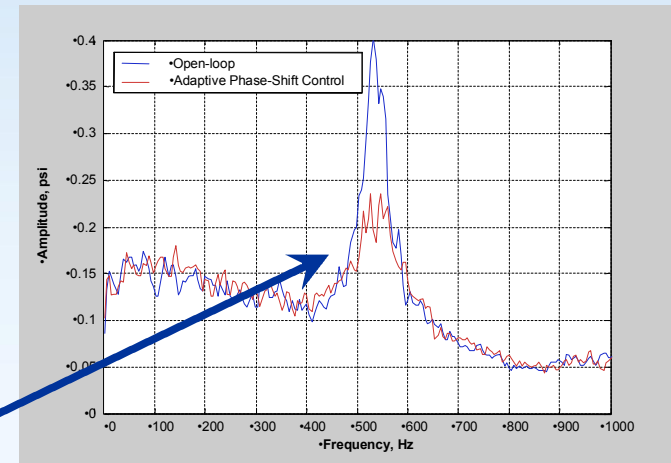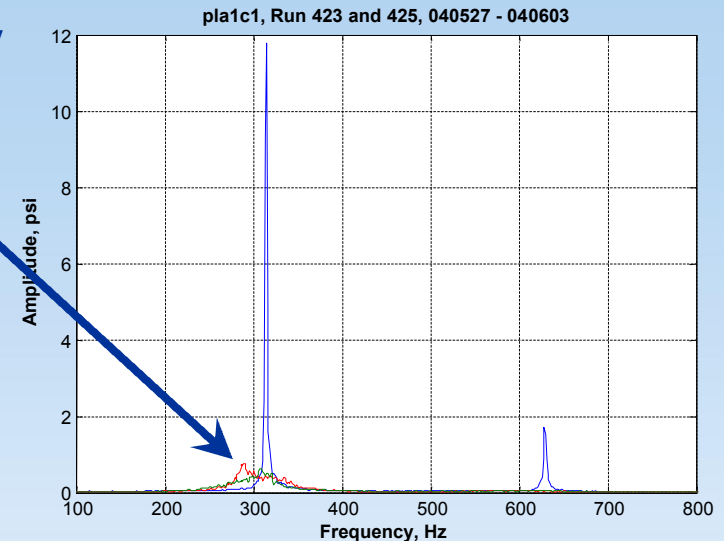
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Active Combustion Control of Instability
Spring 2004

Large amplitude, low-frequency instability suppressed by 90%

pla1c1, Run 423 and 425, 040527 - 040603
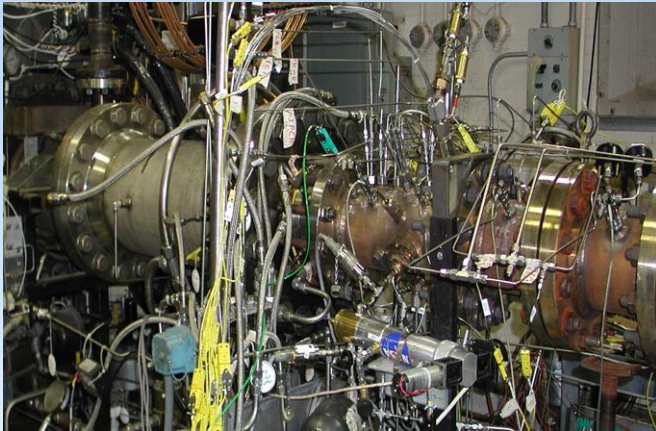
Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows

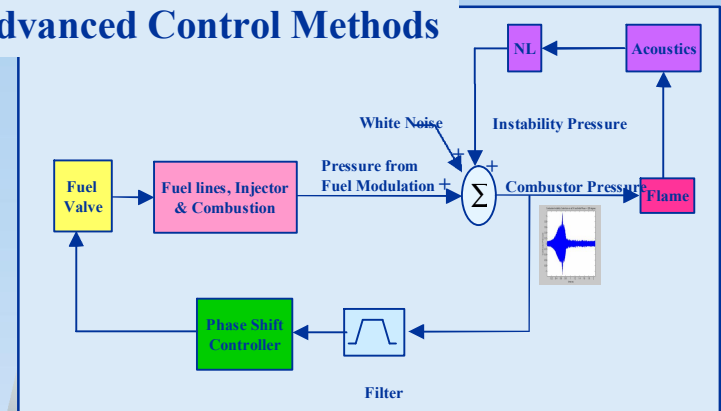**High-frequency, low-amplitude instability is identified, <u>while still small</u>, and suppressed almost to the noise floor.**

Open-loop
Adaptive Phase-Shift Control

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Our Approach: Active Combustion Control Via Fuel Modulation

High-frequency fuel valve

Fuel Outlet (1/4")

Auxiliary Cooling Air (1/4")   Fuel Inlet (1/4")

Advanced Control Methods

NL   Acoustics

White Noise   Instability Pressure

Fuel Valve   Fuel lines, Injector & Combustion   Pressure from Fuel Modulation   Σ   Combustor Pressure   Flame

Phase Shift Controller

Filter

Fuel delivery system model and hardware

Accumulator

Modulating Valve

Modulated Fuel Flow

Fuel In

Fuel Nozzle Assy

Research combustor rig at UTRC

Combustor Instrumentation (pressures, temp's)

Emissions Probe   Fuel Injector

SANITARY SEAL
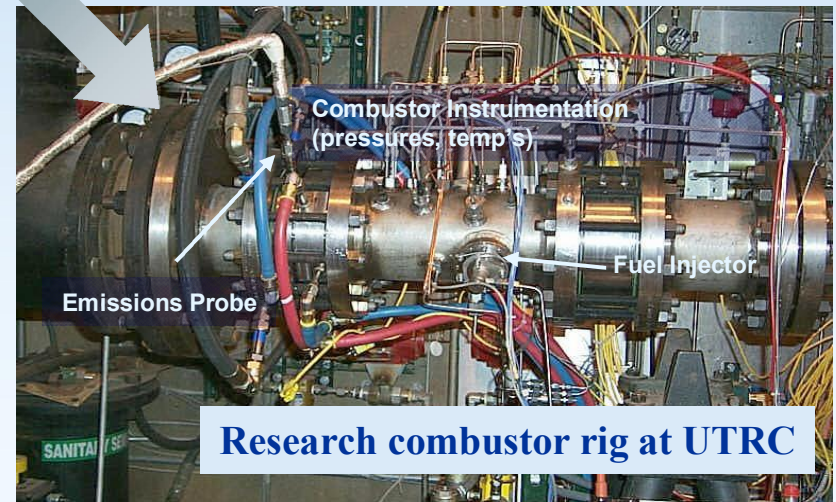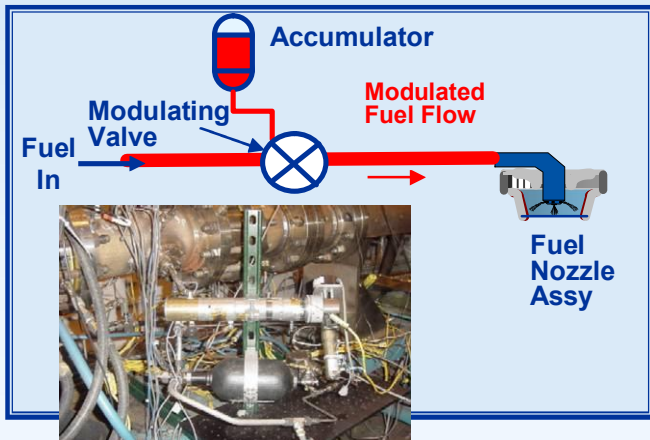
Realistic Engine Hardware Instability Testing

Test Rig Designed to Replicate Real Instability at Engine Conditions

- *Acoustic Analyses Guided Dimensions*
- *Real Engine Lengths, Area Changes, & Flows*
- *Real Engine Components*
- *Instrumentation for steady-state (P,T), dynamic pressure, single-point emissions*
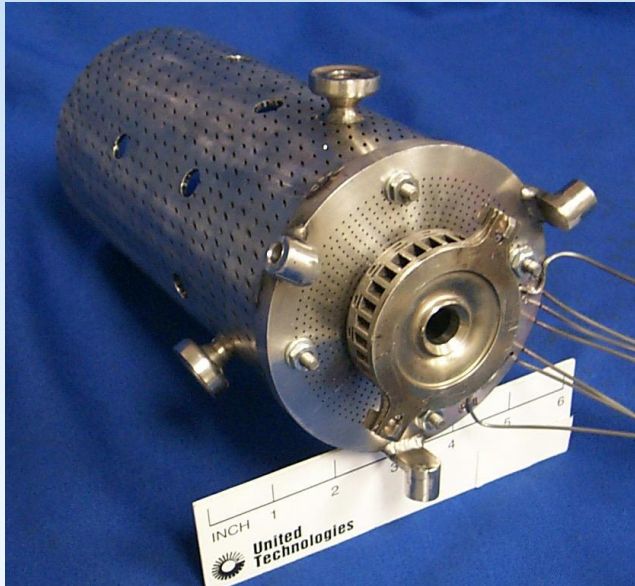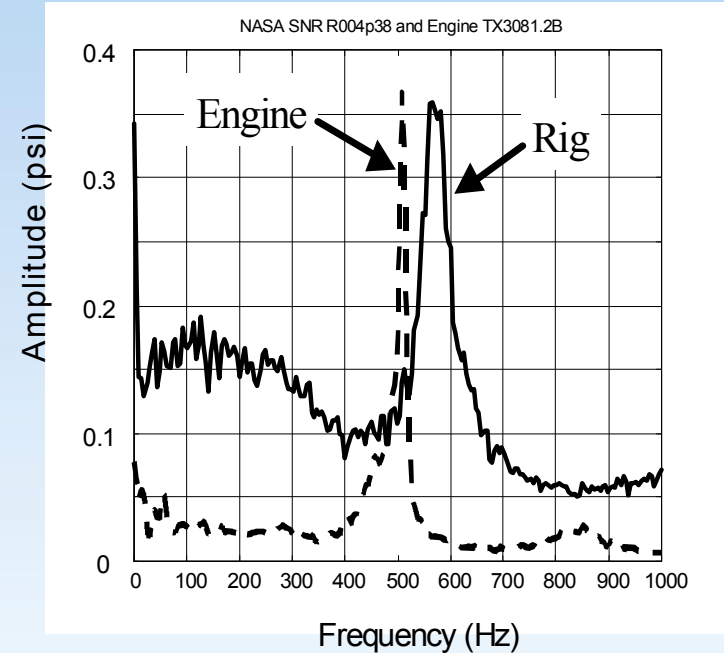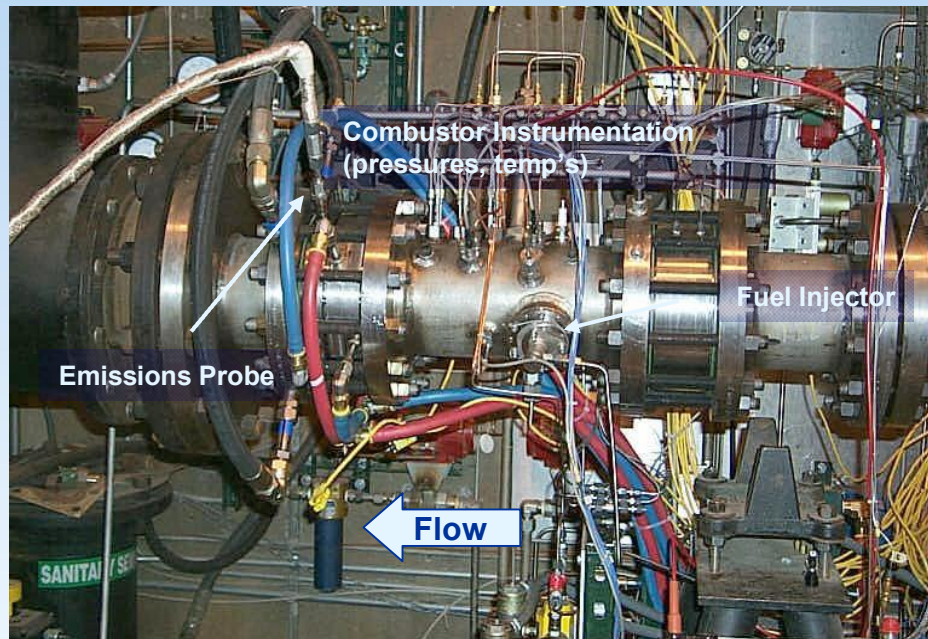

Single-Nozzle Combustor for Instability Research

EMISSION PROBE

FUEL INJECTOR

AIRFLOW ⇨

PRE-DIFFUSER

IGNITOR

WATER QUENCH
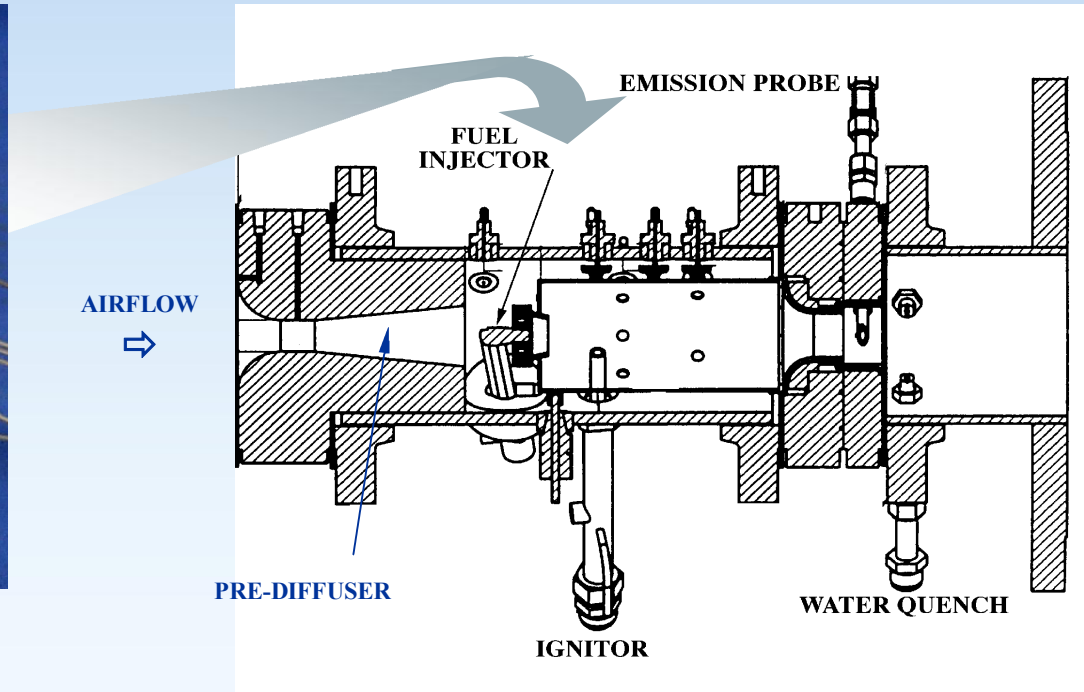
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Combustion Instability Control Testing

Test Rig Designed to Replicate Real Instability at Engine Conditions

Research Combustor Rig at UTRC

NASA SNR R004p38 and Engine TX3081.2B

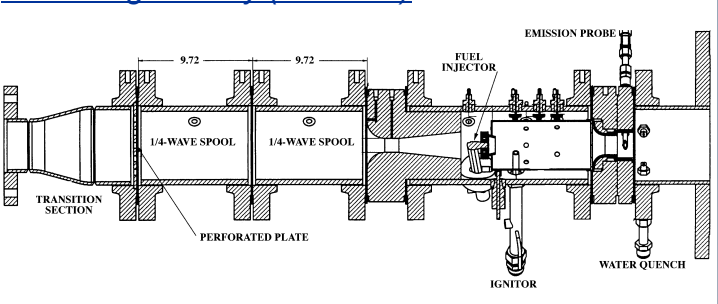Comparison of Engine and Rig amplitude spectra of combustor internal pressure

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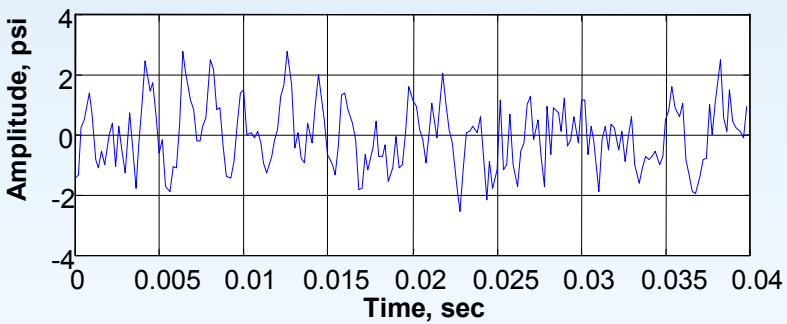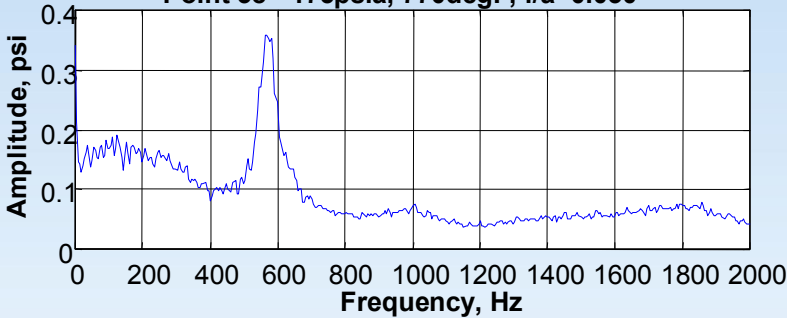# Geometry mod. produced substantial change in instability behavior

## Nominal geometry ("570 Hz")

Alternate geometry ("280 Hz")

Spool sections inserted downstream of the pre-diffuser

- dramatically changes the frequency and amplitude of the instability
- peak amplitude and resonant frequency varied considerably with operating condition and f/a
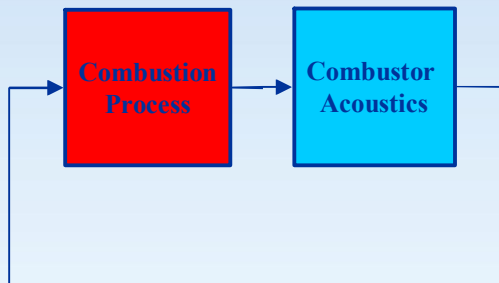 - 2psia to 11psia, 200Hz to 310Hz

PLA1C1: Run4, 990324
Point 38 - 175psia, 770degF, f/a=0.030

PLA1C1: Run6, 990330
Point 40 - 170psia, 781degF, f/a=0.0333
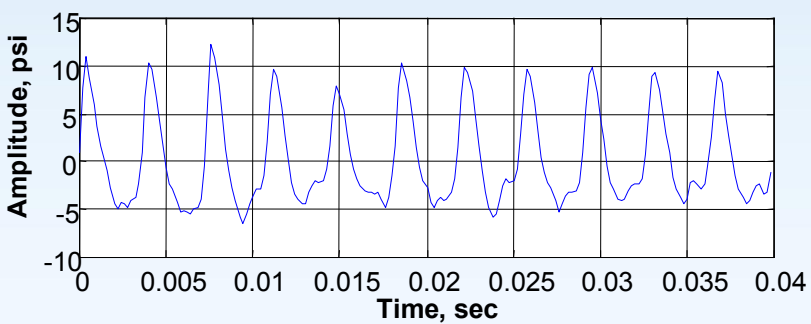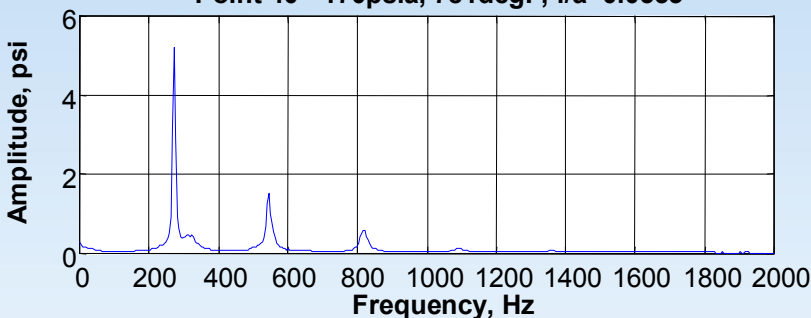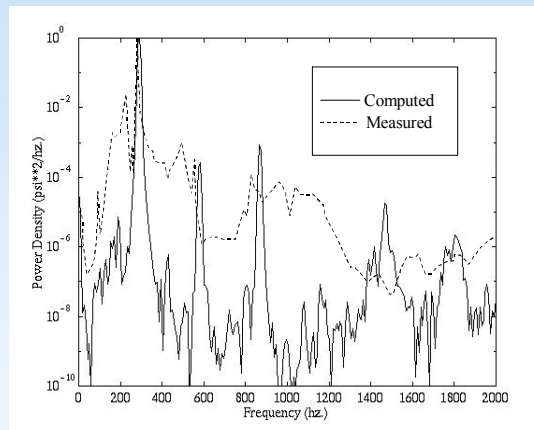
Combustion Dynamics Modeling

Reduced-order oscillator models

Run fast to allow parametric studies in support of control system development
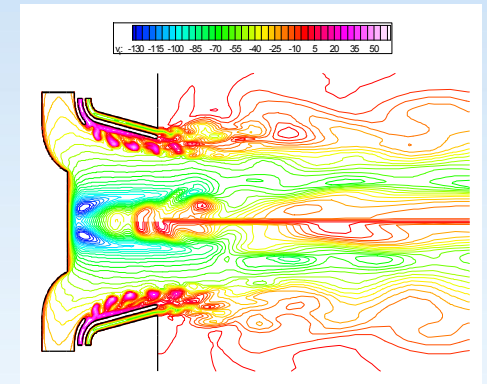
Simplified Quasi-1D dynamic models

Allow physics-based control method validation

Detailed, physics-based dynamic models

Fundamental understanding of combustor dynamics to aid passive, active instability suppression

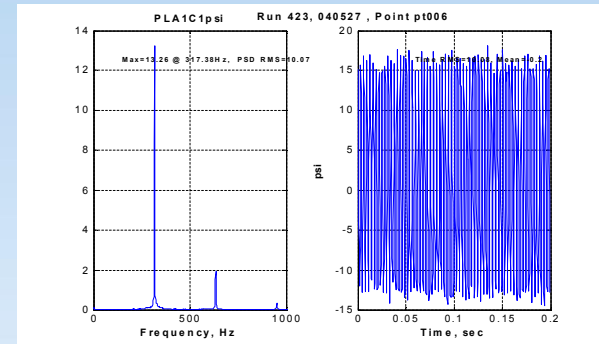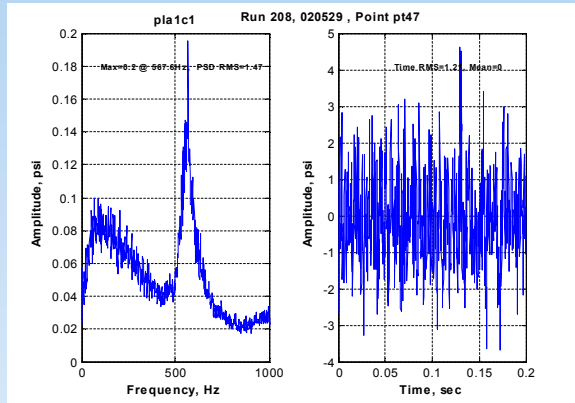*Results from NASA Sectored-1D Model of LPP Combustor Rig*

Penn State Injector Response Model Plot

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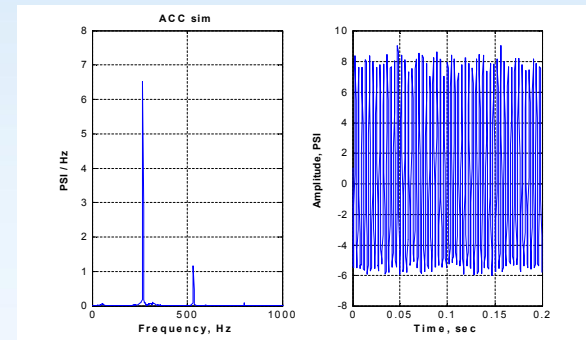
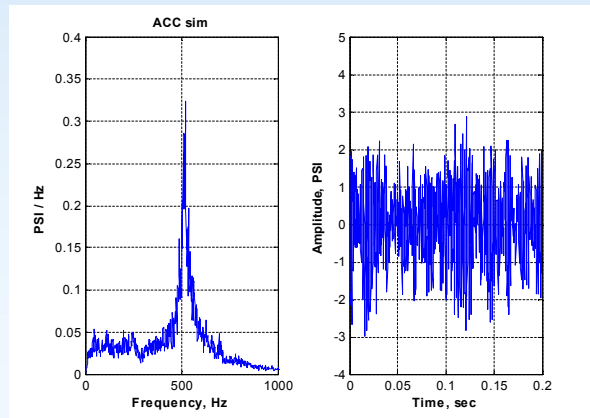# Sectored 1-D Combustion Instability Model – D. Paxson

High-Frequency Configuration
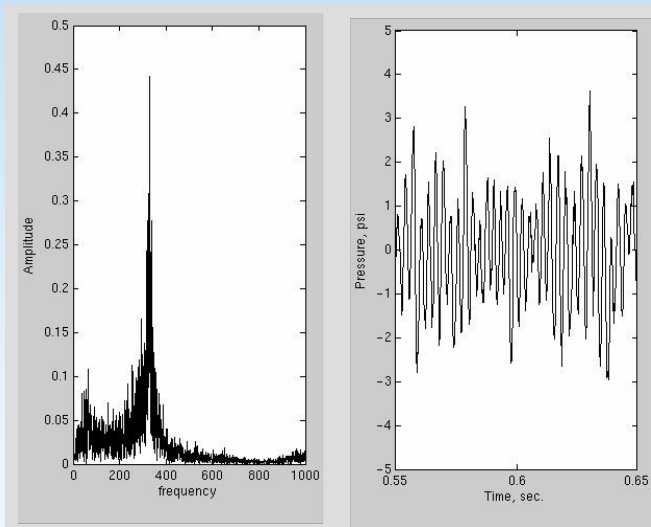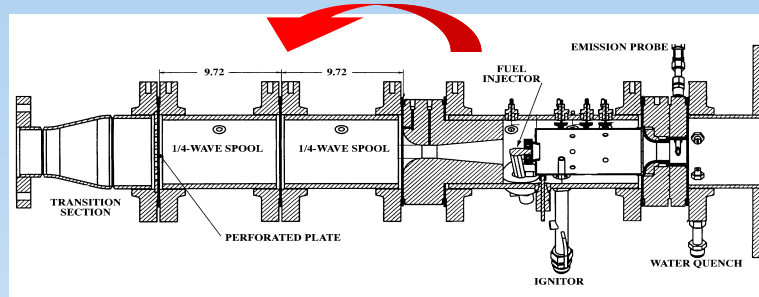
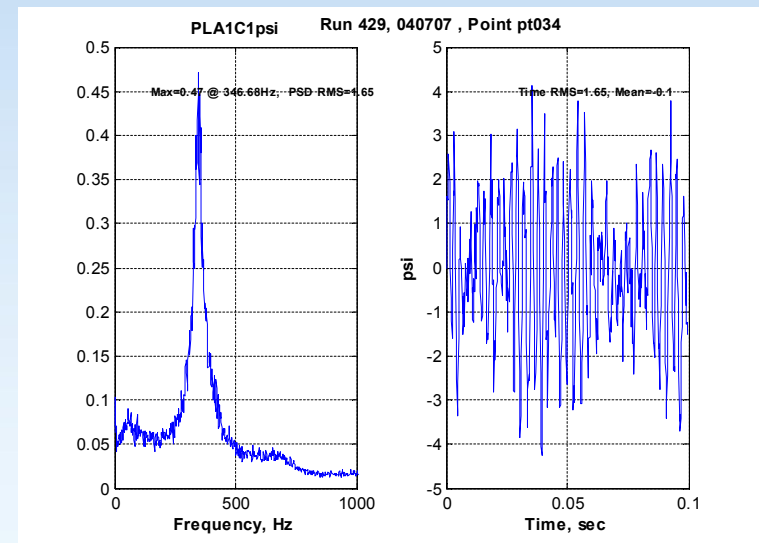Low-Frequency Configuration

Test Rig Data

Simulation Data

Predicted Mid-Length Instability – Sectored 1-D Model

Mid-Frequency
Configuration

Simulation Data

Experimental Data

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High-Bandwidth Fuel Actuator Characterization Testing

Accumulator

Dynamic Pressure Transducers

Pump

Test Valve

P

P

Pressurized Air Volume
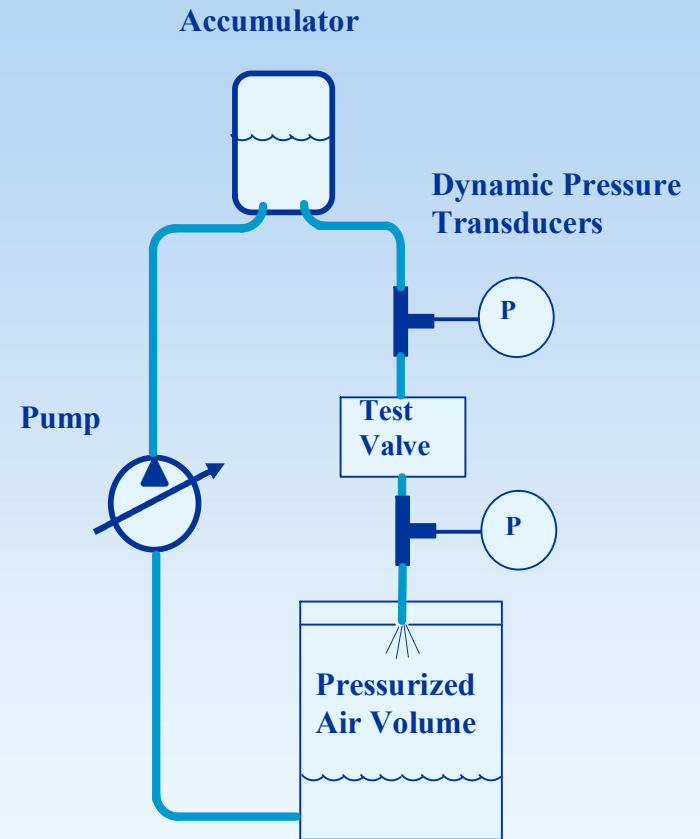
Valve, Feed-system Characterization Rig at NASA GRC

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High-Bandwidth Fuel Actuator

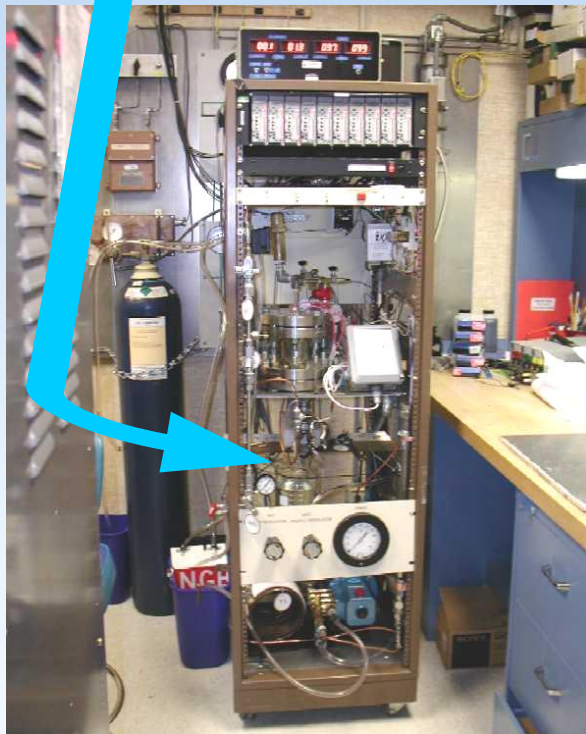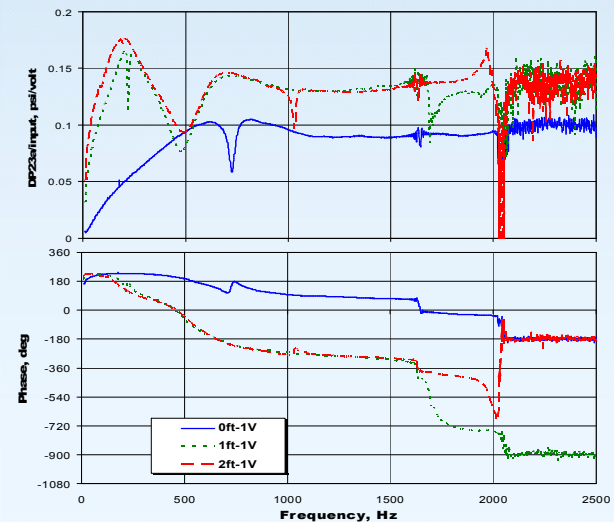**GaTech high-response fuel valve in characterization rig in CE7A**

Steady-State Operational Data
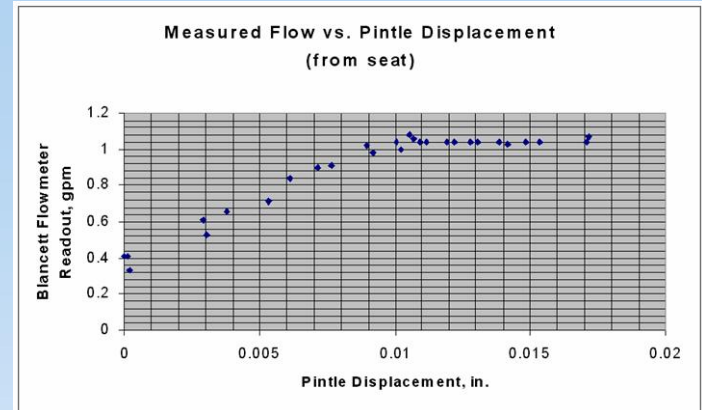
Frequency Response Dynamic Characterization Data
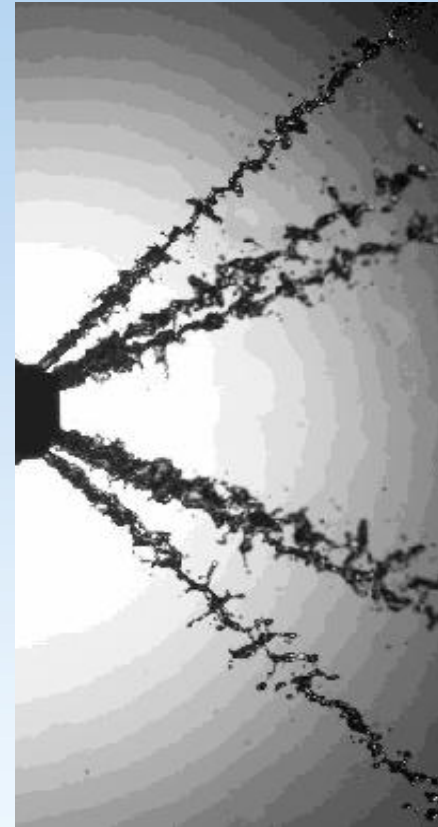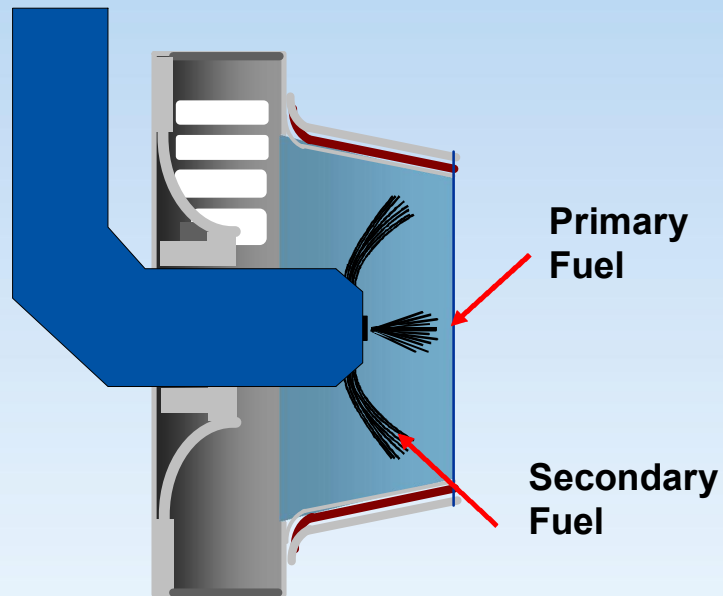
Fuel Delivery System Dynamic Response
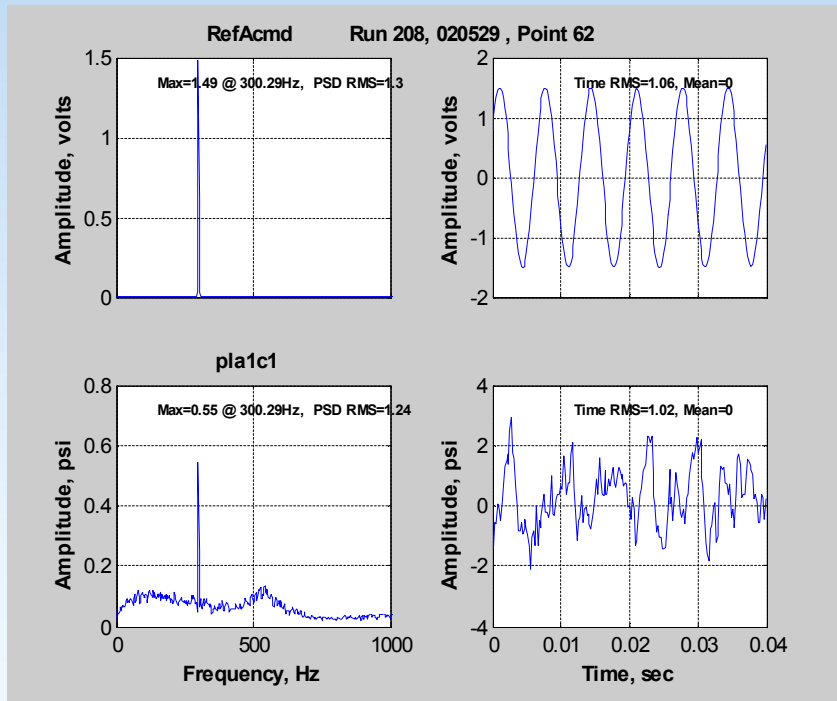

Primary
Fuel

Secondary
Fuel

*Stroboscopic Image of Dynamic
Fuel Injection (courtesy UTRC)*

High-Bandwidth Fuel Actuator

Combustor Pressure Response to Fuel Modulation

300Hz

600Hz
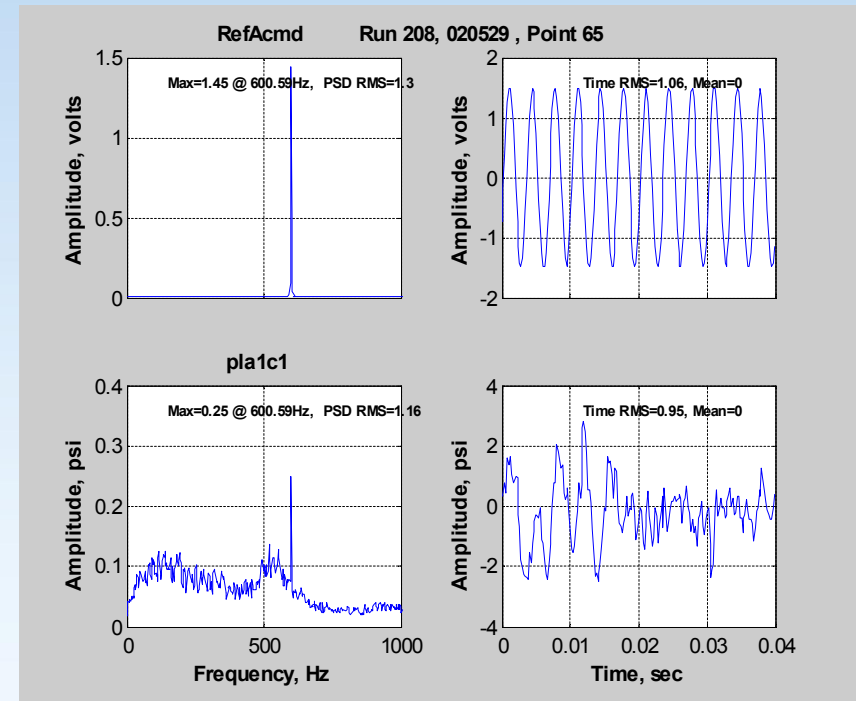
Control Strategies to Deal with Combustion Instability

- Objective
  - Perturb the fuel with the right amplitude and at the right phase to cancel the instability

- Challenges
  - Control action delay, noise, unknown disturbances

- Approach
  - Use reduced-order models for development
  - Use simplified physics-based model for validation before test

- Control methods
  - Empirical: Adaptive phase shifting based on achieved cancellation
  - Model-based: Set the proper phase for cancellation based on a model of the predicted instability and disturbances

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Adaptive phase shifting control:

"Adaptive Sliding Phasor Averaged Control" – G. Kopasakis

Pressure from
Fuel modulation

Overall combustor pressure

Pressure from
instability

Boundary of effective
stability region

Boundary of restricted
control region

NL

Acoustics

Instability Pressure

White Noise

Pressure from
Fuel Modulation

+

+

+

∑

Combustor Pressure

Flame

Fuel
Valve

Fuel lines, Injector
& Combustion

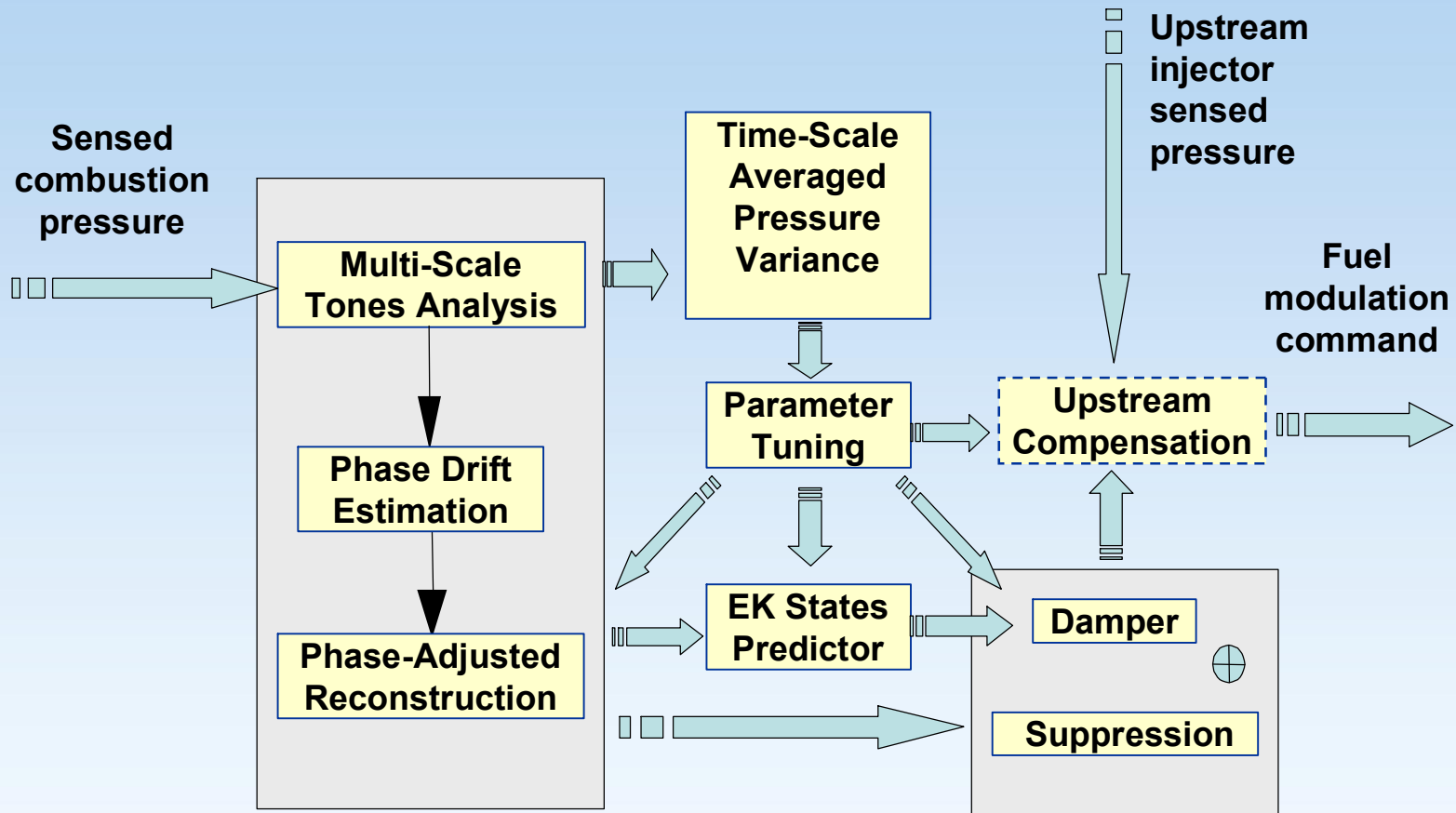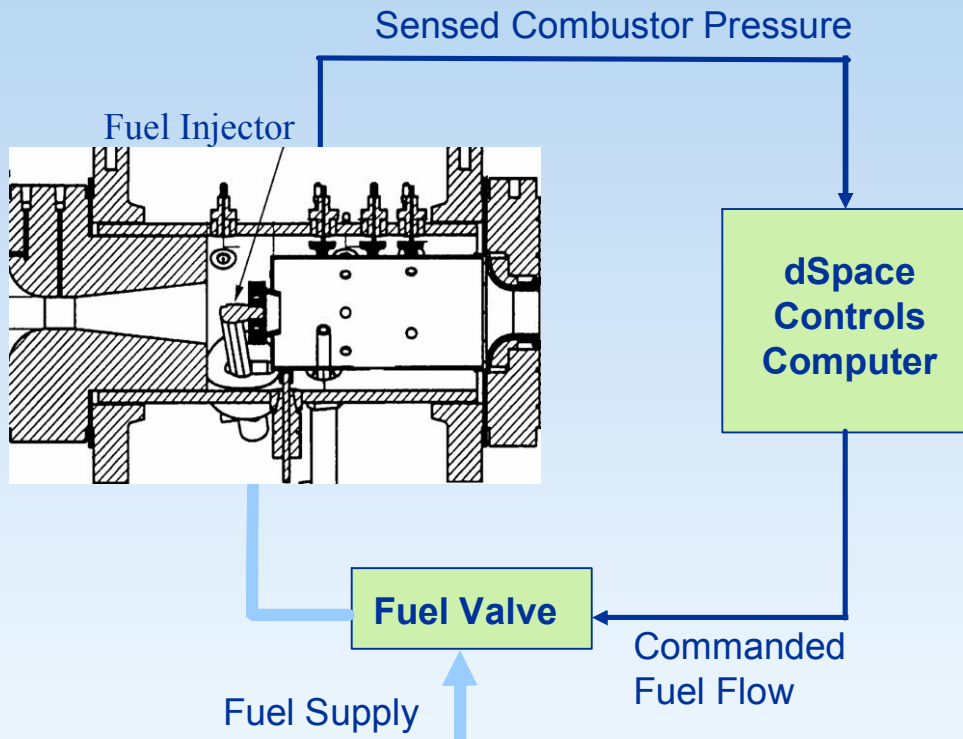Phase Shift
Controller

Filter
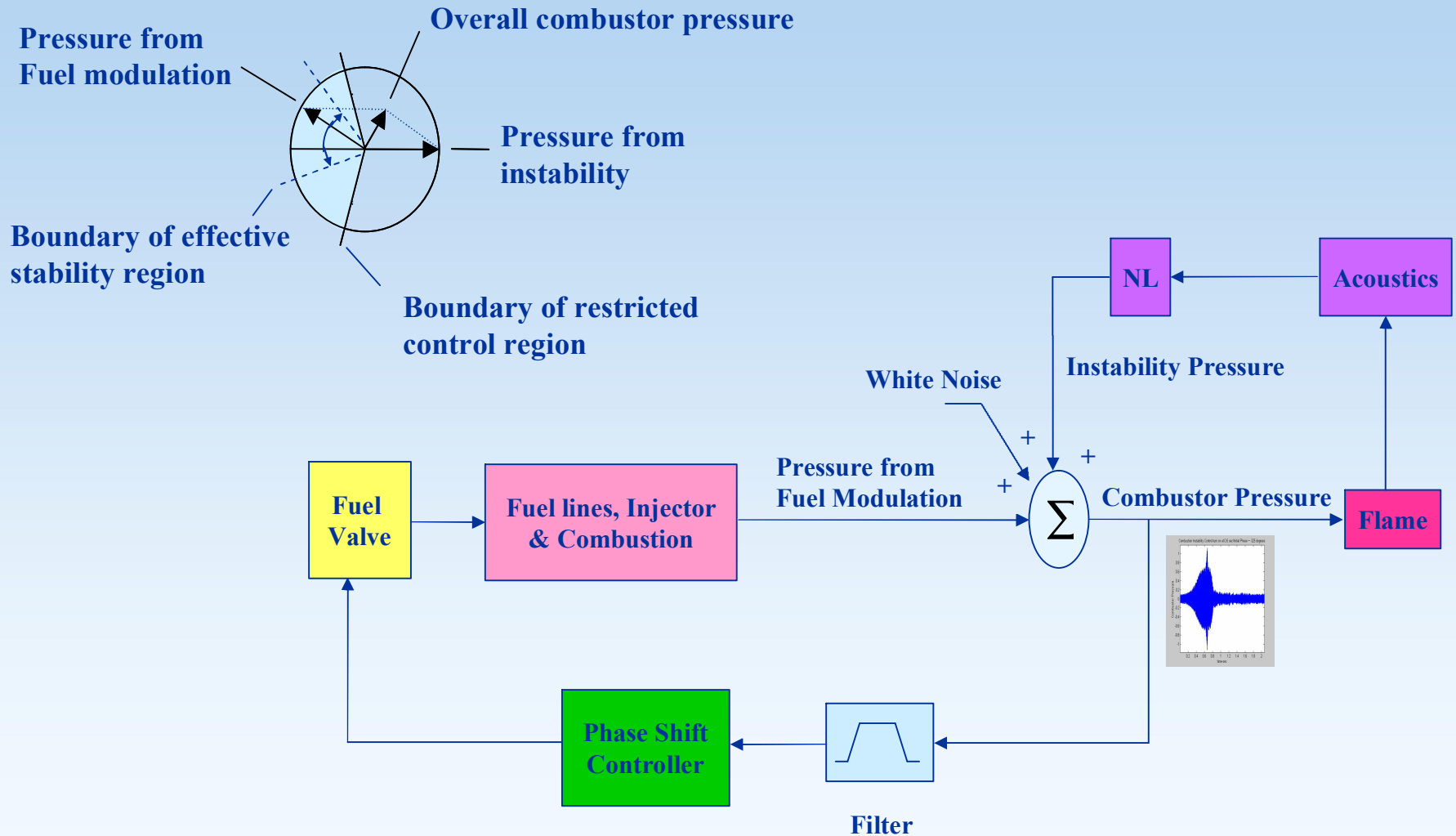
Model-Based Control:

"Multi-Scale Predictive Damper Control" – D.K. Le

Combustion Instability Control Test Implementation

Sensed Combustor Pressure

Fuel Injector

dSpace Controls Computer

Fuel Valve

Fuel Supply

Commanded Fuel Flow

- Control methods implemented in real-time computer

- Rig operated at nominal engine temperature and pressure (P3=175psia, T3=775degF)

- 530Hz resonant frequency related to observed engine instability

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Predicted Instability Control Results: Sectored 1-D Model

Baseline, high-frequency configuration
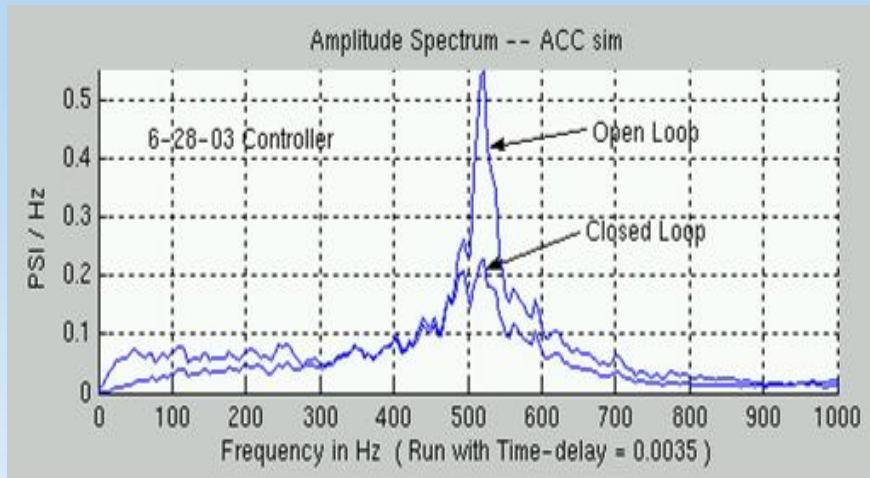
Extended, low-frequency configuration

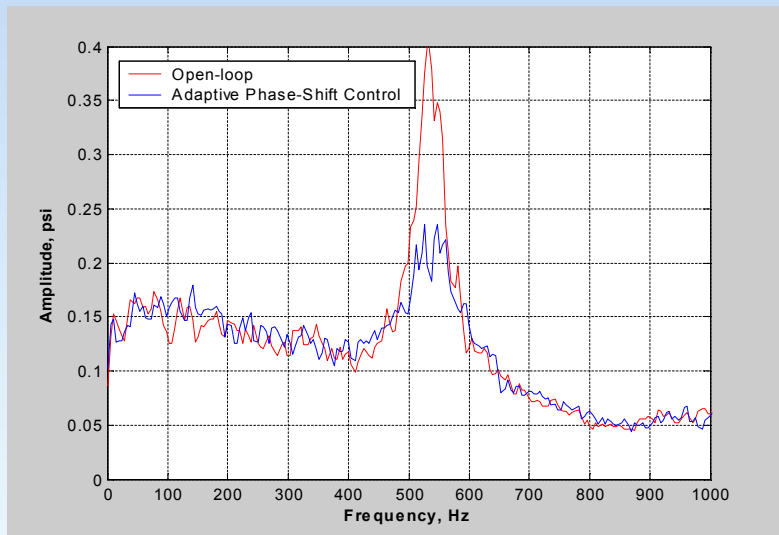Glenn Research Center

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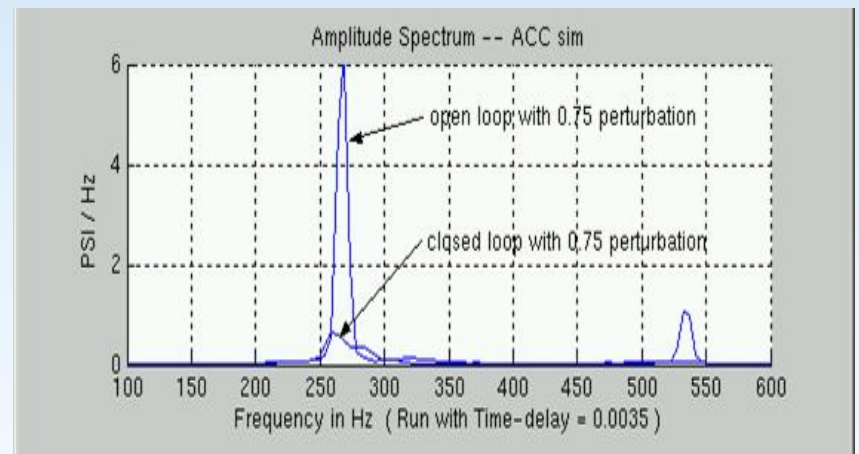
Test Results (*testing done at UTRC, late 2002*):
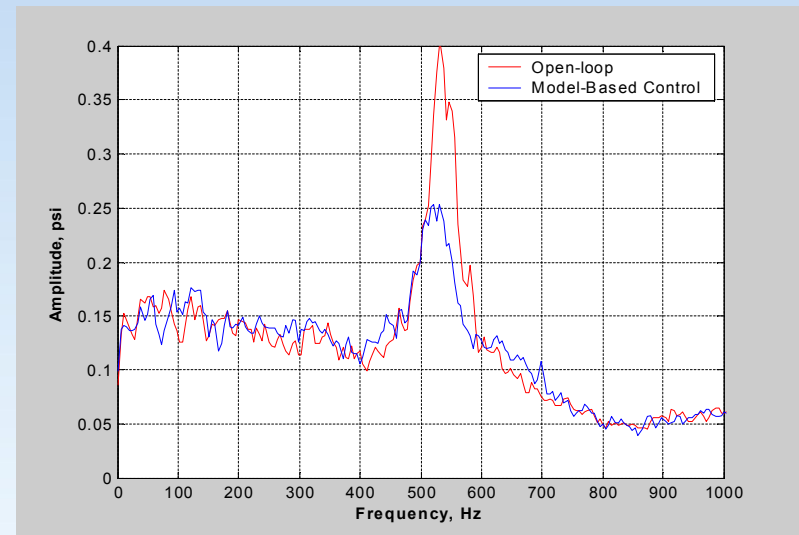
First successful demonstration of combustion instability suppression in a realistic aero-engine environment

-- NASA Team Honor Award--

Adaptive phase-shifting control method

Model-based control method

Experimental Pressure Amplitude Spectra Plots Showing Effects of Active Combustion Control Over Combustion Instability Peak Pressures
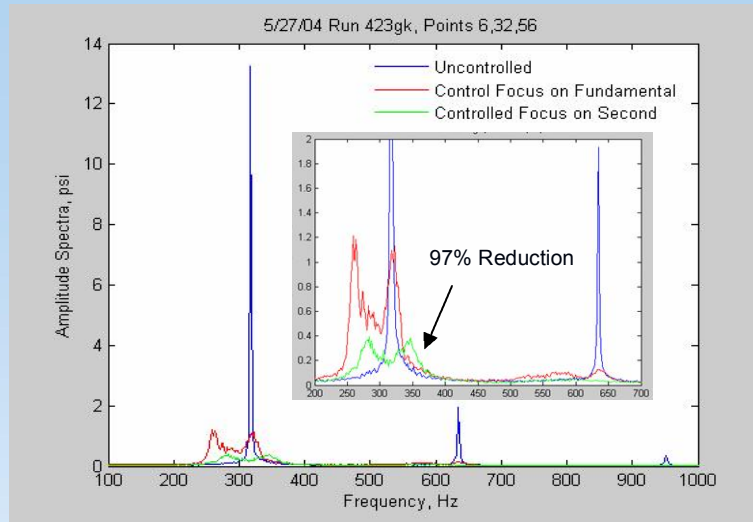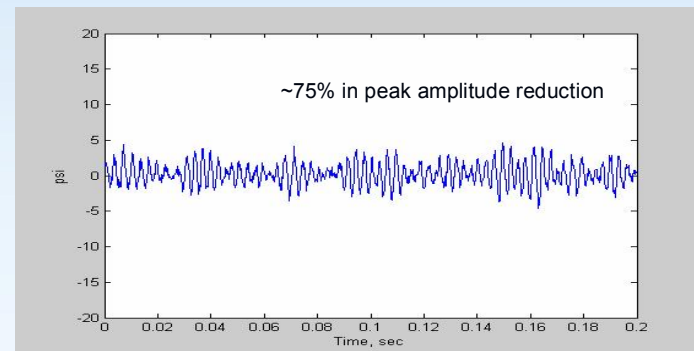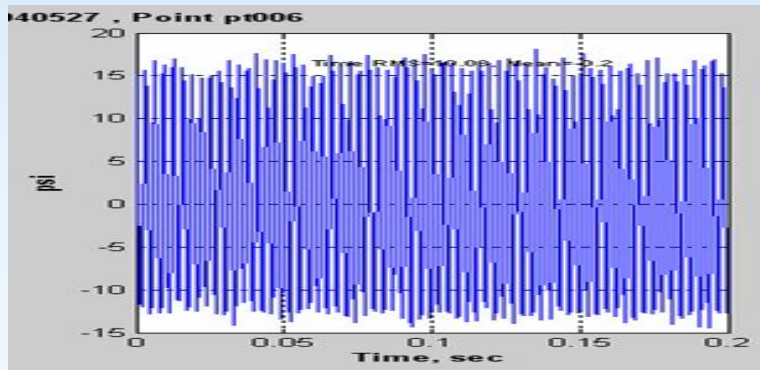
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Test Results *(testing done at NASA, 2004):*

Over 90% reduction in pressure spectral peak for large, low-frequency instability

Uncontrolled –vs- Controlled Instability Pressure

<u>Summary</u>

- **Combustion instability control successfully demonstrated in a realistic aircraft engine environment for two different combustor configurations**

- **In-house capability for actuator design, modeling methods, control methods, combustor dynamics testing**

- **Technology Transfer:**

    – **Publications:**

        - **10 NASA-authored / co-authored conference papers and TM's**

        - **Sponsored ~20 university-authored papers and journal articles**

        - **3 invited presentations to industry / academia groups**

        - **2 contractor reports**

        - **7 R&T Reports articles**

        - **AIAA book chapter co-authored by Pratt and NASA**

    – **Application of technology:**

        - **GE considering NASA models and control methods for use with an advanced combustor design (Prop 21)**

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at Lewis Field

Future Plans

- **Integrate controls, combustor design, sensor, and actuator technologies to provide:**

  - **Intelligent fuel/air management system with temporal and spatial fuel modulation for**

    - **Instability suppression**
    - **Pattern factor control**
    - **Emissions minimization**

  - **to enable…**

  - ➤ **Combustor with extremely low emissions throughout the engine operating envelope**